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SOME REMOTELY CONTROLLED MASTER-SLAVE MANIPULATOR DESIGN PROBLEMS

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ABSTRACT. A number of specific requirements for designing remotely controlled master-slave manipulators, including the kinematics and the dimensions of the master and slave members, are presented. General requirements for master-slave manipulator control systems are discussed.

A number of specific requirements, determined by the following factors, must be considered when designing remotely controlled master-slave manipulators: (a) the types of operations the manipulator must perform; (b) the peculiarities of the human operator, the working movements of whose hands are copied by the manipulator slave elements; (c) the kinematics and dimensions of the manipulator master and slave elements. It is the second and third factors that permit the formulation of certain general requirements for master-slave manipulator control systems. /17

Peculiarities of the Human Operator Considered in Designing Master-Slave Manipulators

Master-slave manipulators, as distinguished from other types, should, to a considerable degree, correspond to the anthropometric and physiological peculiarities of the human operator performing the control function. We shall consider only certain of these peculiarities with significant effect on the properties of master-slave manipulators.

Kinematics of the Human Arm

A number of authors have written of their studies of the kinematics of the human arm. However, reference [1] is the most meaningful from the point of view of manipulator design, pointing out that the human arm can be depicted as an open kinematic chain with 12 degrees of freedom. However, the total number of degrees of freedom in the kinematic chain of the human arm can be reduced to nine, I-IX (Figure 1), if we consider the shoulder joint immobile. We will consider this scheme of the kinematic chain as the original one in determining the kinematics of manipulator master and slave elements.

The Operator's Work Zone

Knowing the kinematic peculiarities, and the typical dimensions of the human arm as cited in reference [2], we obtain the limits of the zone in which the

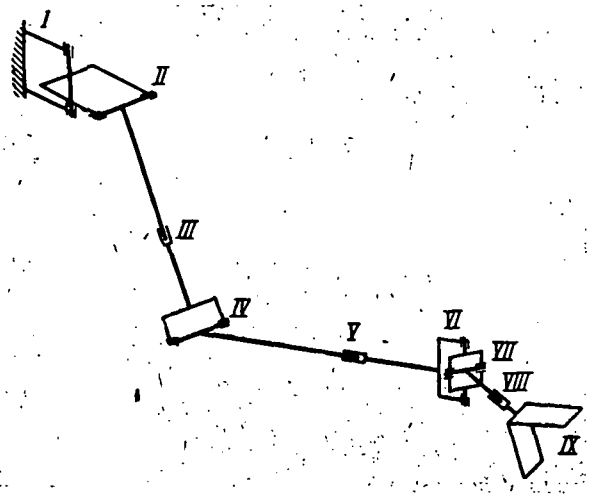

Figure 1.

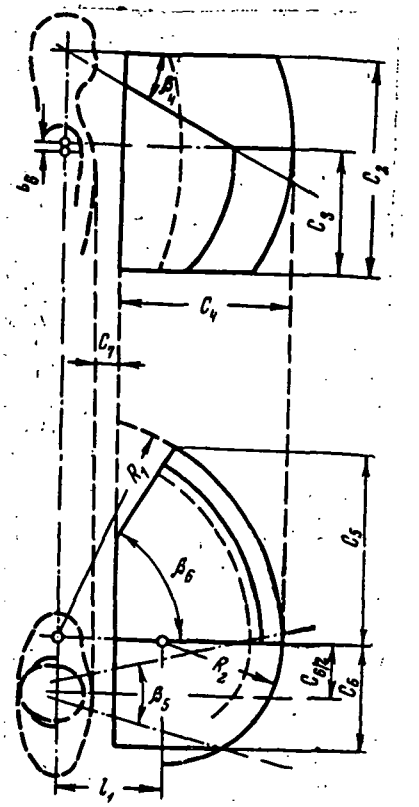

Figure 2. The arm's normal work zone.

$\beta_4 = 30°$; $\beta_5 = 30°$; $\beta_6 = 60°$; $c_2 = 679$; $c_3 = 360$; $c_4 = 520$; $c_5 = 590$; $c_6 = 315$; $l_1 = 326$; $l_8 = 25$; $R_1 = 643$; $R_2 = 367$; $c_7 = 10 \div 50$

operator can work, in which objects can be gripped. Reference [3] notes that from the physiological point of view it is undesirable to use all of the zone when working. The least fatiguing movements prove to be those in which only the forearm, hand, and fingers participate. The whole arm, up the shoulder, moves when the work cycle is short (1-2 minutes) and short rests are permitted. The shoulder joint should not move during work movements. As a result, we can distinguish the arm's so-called normal work zone (Figure 2). /18

The space occupied by the operator's body and head should be made inaccessible to the master element for safety reasons by providing a space of to 5 to 10 cm between the zone in which the master elements work and the body when control systems are used under conditions when there is active force reflection. The height of the work zone depends on the working operations to be performed and can be selected equal to the height of the forearm, or of the eyes, above the lower limit of the zone. The complex form of the upper limit of the work zone is explained by the fact that the spatial area within the operator's field of view is not in the work zone.

The determination of the normal work zone, in addition to purely physiological factors must include operator working conditions when, because of cramped quarters, or because his attitude makes it inconvenient for him to move his arms, the zone can be quite restricted. This is typical, for example, of deep submergence vehicles.

Knowing the operator's normal work zone, let us determine the scaled work zone for the manipulator slave elements. We will understand this to mean the reduced (increased) copy of the given work zone for the slave elements completely inscribed in the volume of the operator's normal work zone. The master element tongs (the operator's hand) will move within the limits of the scaled work zone for the slave element. The scale factor, K_s, equal to the ratio of the linear dimensions of the scaled work zone and the given work zone for the slave elements determines the ratio between the linear dimensions of master and slave elements of the master-slave manipulator. /19

The Nature of Movements of the Hand of an Unloaded Arm

According to existing systems for classifying man's work movements [4], any work operation can be made up of a limited number of elementary movements. Of the elementary movements characteristic of working with master-slave manipulators, the precise (careful) movement of the hand without a load to a specific point in space has the greatest velocities and accelerations. The purpose of the movement is determined by the operator. A series of experiments was conducted under the conditions listed to determine the nature of hand movements. Figure 3a shows the results for the range of change in arm trajectories obtained in the different experiments, and the averaged trajectory. Figure 3b portrays the experimentally obtained trajectories for different distances between the initial and end points of hand movement. We see (1) the operator's hand movements are monotonic, (2) that the acceleration processes are the same for the majority of the reactions, (3) that the speed of movement remains constant over the mean section of the trajectory when hand movement is more than 2 to 3 cm, (4) and that the greatest scatter in the nature of the reactions is observed over the braking portion, where the type of trajectory is determined by the purpose of the movement and the operator's state of training.

The results agree well with the results of the investigation of the hand

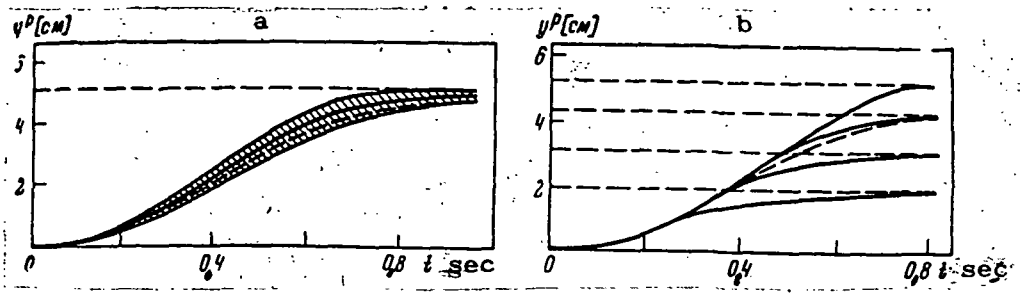

Figure 3. Change in arm trajectory.
a - range of change in trajectories; b - trajectories for different distances between the beginning and end points of hand movements.

movements of an operator's unloaded arm when the purpose of the movement is assigned by the experimenter. As reference [5] points out, the movement process in this case has the form shown in Figures 3a and 3b by the dashed line, and is described by the expression

$$Y^p = L[1 - (1 + 6t + 18t^2)e^{-6t}], \quad (1)$$

where L is the distance the hand moves. The different nature of the braking portions evidently can be explained by the different goals assigned the operators in the experiments. The indicated differences are insignificant, so when L = 5 cm, Eq. (1) can be used to describe the acceleration and deceleration processes in our case, too.

Having ascertained the nature of the hand movements of an unloaded arm, we have determined the type of input action for master-slave manipulator control systems.

Kinematics of Master and Slave Elements of Master-Slave Manipulators /20

The kinematic scheme for master and slave elements of master-slave manipulators should meet the following requirements: (1) ensure the reach of the tongs of the master or slave element to any point in the work zone and the orientation of the tongs as necessary at each of these points; (2) provide the operator with the ability to control all the degrees of freedom of the master slave elements; (3) ensure the absence of intensive moments of the intermdiate kinematic links between the point where the kinematic chain is attached and the tongs of the master or slave element with change in orientation of the tongs at any point in the work zone; (4) when obstacles are present in the work zone of the slave

elements which hinder access to individual points in the zone, ensure mobility of individual kinematic links when the tongs are fixed that will establish the maneuverability of the manipulator [6]. Let us examine possible variants of kinematic diagrams for the master and slave elements of master-slave manipulators.

The Kinematic Scheme When Following the Positions of the Operator's Shoulder, Forearm, and Hand

The master element of the master-slave manipulator, which follows the position of the operator's shoulder, forearm, and hand, is fastened to the operator's shoulder girdle. The kinematic scheme for master and slave elements is similar to that of the human arm and has nine degrees of freedom, including the degree of freedom for the tongs (see Figure 1).

The point at which the master element is attached to the operator's girdle is movable in space, so the one-to-one correspondence between positions of master and slave will be constantly disrupted (the point of attachment of the latter is stationary relative to the body of the manipulator carrier. Therefore, in existing manipulator designs every effort is made to keep the point of attachment of the master element stationary in space, and this often restricts the capacity to follow the positions of the operator's hand, or of his forearm and hand.

The Kinematic Scheme When Following the Position of the Operator's Hand

The master element following the position of the operator's hand has a number of advantages as compared to the variation examined above: the point of attachment of the master element is stationary in space; the number of degrees of freedom of the master element can be less than the number of degrees of freedom of the human arm itself; there is no need to match the master element to the individual features of the arm of a specific operator; the operator's arm can be freed from the master element very simply and quickly.

The movement of the tongs within the limits of a specified work zone is possible with the help of a kinematic scheme that contains a minimum of three degrees of freedom characterizing either translation, or rotative, motion. Figure 4 shows eight possible variations in the position of degrees of freedom I, II, and III in the kinematic chain of the master or slave element. Some are widely used in existing manipulators. The difficulties in obtaining extensive translation motions have led to the use of a kinematic scheme with

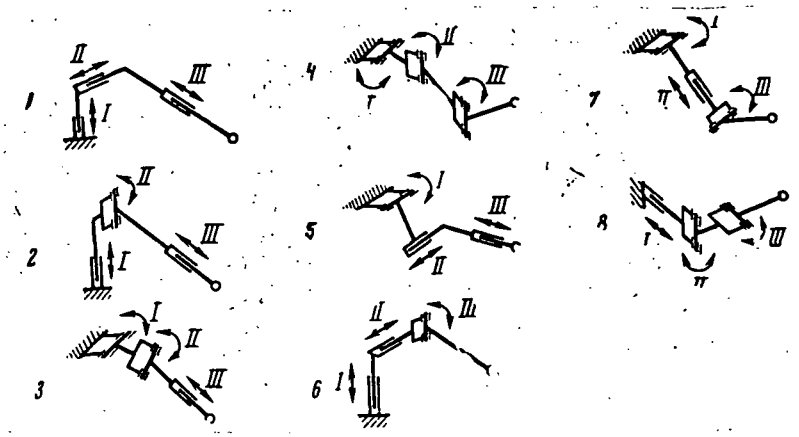

Figure 4.

eight degrees of freedom, obtained from the scheme in Figure 1 by the exclusion of the degree of freedom for the rotation of the shoulder (III) and which, consequently, is variant 4 in Figure 4. /21

Let us consider another possibility for reducing the number of degrees of freedom in the kinematic scheme for master and slave elements, that of excluding, from the scheme in Figure 1 the degrees of freedom of rotation of the tongs (VIII) and rotation of the forearm (V). Figure 5a shows this kinematic scheme (the numbers of the degrees of freedom I, II, III, IV, VI, VII, IX, here and in subsequent variants of simplified kinematic schemes correspond to the numbers in Figure 1). Here rotation of the tongs is possible only when its position is completely determined, that is, when the axis of rotation passes through the point at which the master element is attached, and we now will say the tongs have selective rotation. Intensive movements of the shoulder and forearm of the master and slave elements will be observed upon rotation, and the elbow hinge will describe an arc equal to the angle of rotation. The two shortcomings noted are substantial and limit the use of the simplified variant considered.

Inherent in the kinematic scheme that results upon the elimination from the kinematic scheme in Figure 1 of the degree of freedom of rotation of the tongs (VIII), and of one of the degrees of freedom causing it to adduct-abduct, or flex-extend, (VI) or (VII), are the same shortcomings noted for the preceding simplified scheme, except for the fact that the tongs have two selective rotations.

The addition of the freedom of rotation of the tongs (VIII) returns to both variants the possibility of arbitrary orientation of the tongs to any

point in the work zone. But if the longitudinal axis of stationary tongs passes through the point at which the master (slave) element is attached, the elbow hinge will be able to move in an arbitrary manner along a circle with its center in the longitudinal axis of the tongs, that is, the kinematic scheme has one degree of maneuverability. This indicates that a certain class of kinematic schemes has the property of selective maneuverability because the presence, or absence, of maneuverability is determined by the position of the tongs in space.

If the master element following the position of the operator's hand has one degree of maneuverability for arbitrary orientation of the tongs (Figure 1), or selective maneuverability (Figure 5b), the operator cannot control the position of the shoulder hinge by moving the tongs. Any external influence on the master or slave element (the element's own weight, contact with foreign objects, hydrodynamic forces) will cause the elbow hinge to move. Such movement usually is undesirable, and sometimes even is dangerous for the operator, and for objects in the work zones. Thus, it is possible to control all degrees of freedom of the master element following the position of the operator's hand if its kinematic /22 chain does not have a single degree of maneuverability.

Complete lack of maneuverability while retaining the ability to orient the tongs arbitrarily to any point in the work zone can be obtained from the above-considered simplified variants of the kinematic scheme (see Figure 1) only by eliminating the shoulder rotation degree of freedom (III) and providing for two degrees of freedom (I and II) in the shoulder hinge so the shoulder can swing (Figure 6, modification I). The hand joint can be made with modifications 1, 2, and 3 in Figure 6. Selection of the particular modification depends on providing the necessary orientation of the tongs with the gearing and motors used in the control systems.

Figure 5c is a kinematic scheme that differs little externally from that portrayed in Figure 6, modification 1. The only difference is that the axis of rotation of one of the degrees of freedom of the shoulder hinge passes through the work zone of the master (slave) element; that is, the shoulder hinge imparts rotation and swing to the shoulder. The result is to give the kinematic scheme selective maneuverability; that is the kinematic schemes in Figure 6 are suitable /23

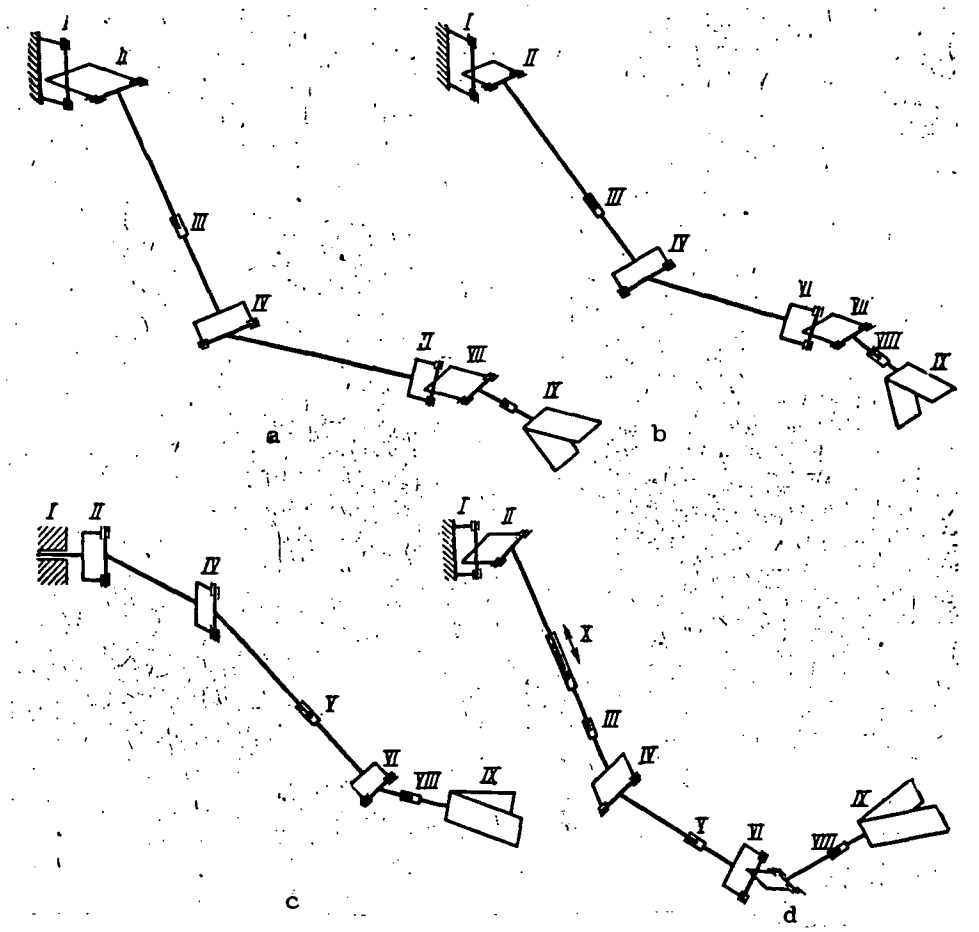

Figure 5. Kinematic schemes in which the number of degrees of freedom change (see Figure 1). a - kinematic scheme obtained by the elimination from the scheme (see Figure 1) of degrees of freedom V and VIII; b - kinematic scheme with selective maneuverability; c - kinematic scheme in which the shoulder hinge communicates rotation and swing to the shoulder; d - kinematic scheme with ten degrees of freedom.

for use in the master and slave elements of master-slave manipulators that follow the position of the operator's hand if the axes of rotation of the degrees of freedom of the shoulder hinge (I and II) do not intersect the work zones.

Kinematic Scheme When Following the Positions of the Operator's Forearm and Hand

The need to preserve the maneuverability of the master and slave elements of a master-slave manipulator when the operator must be able to control all the degrees of freedom in their kinematic schemes requires that the positions of the operator's forearm and hand be followed. If the point of attachment of the

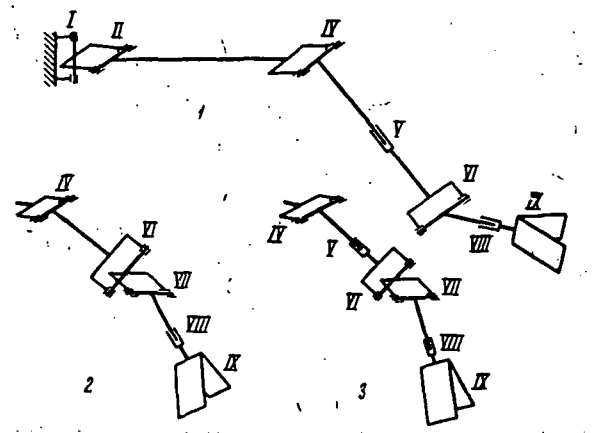

Figure 6.

master element is not at the operator's shoulder girdle, the positioning of the elbow hinge of the master element at any point in space accessible to the elbow joint of the operator's arm can be accomplished by three degrees of freedom with rotational or translational movements, variants in the disposition of which are presented in Figure 4. The kinematic scheme shown in Figure 5d, for example, can be used to follow the positions of the operator's forearm and hand in a mockup of a master element designed to investigate the motion parameters of the human arm [1]. The number of degrees of freedom in the master (slave) element of a master-slave manipulator in this case is 10.

Thus, if there is no need for the slave elements of a master-slave manipulator to have maneuverability, it is desirable to use the master element to follow the position of the operator's hand and to use a kinematic scheme with seven or eight degrees of freedom (Figure 6). If the slave elements must be maneuverable, the master elements must be selected on the basis of the need to follow the positions of the operator's forearm and hand, and the number of degrees of freedom in the kinematic scheme is increased to 10 (see Figure 5d).

Dimensions of the Master and Slave Elements of Master-Slave Manipulators

The original data for determining the dimensions of the mater and slave elements are: the kinematic scheme selected for the master and slave elements; the dimensions of the work zone for the slave elements; the dimensions of the normalized work zone for the slave elements, or the magnitude of the scale factor K_s; the position of the points of attachment of the slave elements relative to the work zone; the possible orientation of the tongs at each of the points on the boundary of the work zone, determined by manipulator working conditions and the list of work operations; the dimensions of the hand kinematic link of the slave element, determined during the draft design study state and based on the condition that here the arrangement of the slave elements and gearing

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will provide specified forces for compressing and rotating the jaws of the tongs.

Dimensions of Master and Slave Elements for Following the Position of the Operator's Hand

If the master and slave elements of a master-slave manipulator follow the position of the operator's hand, the dimensions of the slave element are established first.

Knowing the magnitude of the work zone for the slave element, the dimensions of the hand kinematic link, and the necessary orientation of the tongs at each point on the boundary of this work zone, we select the region in space in which the hand hinge is located when performing the operations. Let us determine the dimensions of the shoulder and forearm of the slave element. Because its kinematic scheme has no degree of freedom for rotation of the shoulder, movement of the forearm relative to the shoulder is possible only in the plane in which the longitudinal axes of these kinematic links are located. The cross section of this plane of the three-dimensional figure formed as the end of the forearm (hand hinge) moves is a part of a circular ring (Figure 7). The following designation are used in the figure: OA is the internal radius; OB is the external radius; OC is the length of the shoulder; BC is the length of forearm; δ_{El} is the angle of rotation in the elbow hinge; δ_{Sh} is the angle of rotation in the shoulder hinge (central angle of the circular ring); δ'_{Sh} is the complementary angle of rotation in the shoulder hinge because of movement of the forearm; γ is the auxiliary angle.

Parameters OA, OB, and δ_{Sh} are determined by the location of the point of attachment of the slave element relative to the work zone and the magnitude of the region in space in which the hand hinge is located when performing work operations.

The calculations include the determination of the shoulder and forearm dimensions for given angles of rotation, δ_{El} and δ'_{Sh}. Analysis of all possible variants involves a great many calculations, so a simplfying nomogram shown in Figure 8a, has been developed. The sequence in which the nomogram is used is as follows:

we lay off the value of angle δ'_{Sh} on scale 1, and on scale 2 read the points corresponding to the dimensions (OA + OB) and (OB - OA); we read the magnitude of

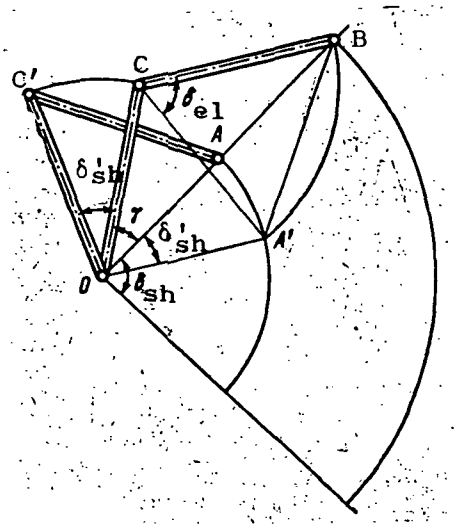

Figure 7.

the difference in angles OA'B and OBA' off irregular scale 3 (Figure 8b);

we read the magnitude of angle OA'B off scale 4 (see Figure 8b);

setting dimension OB, we read dimension A'B from scale 8 (see Figure 8b);

setting the angle of rotation of the elbow hinge, δ_{El}, we read the dimension of the forearm BC from scale 7 (see Figure 8c); /26

going back to scales 1 and 2, we lay off ($\angle OA'B - \angle CA'B$) and (BC $\pm$ OA') (see Figure 8d);

we read angle ($\delta_{Sh} + \gamma$) from scale 4 (see Figure 8d);

we read the shoulder dimension OC from scale 8 (see Figure 8d).

Figures 9a and b show the results of the calculations of slave element shoulder and forearm dimensions for different values of angles of rotations, δ_{El} and δ'_{Sh} for OA/OB = 0.5.

Let us determine the dimensions of the master element of a master-slave manipulator. The dimensions of its kinematic links are equal to those of the kinematic links of the slave element multiplied by the scale factor K_s. The angles of rotation in the hinges of the master and slave elements are the same. The distance between the points of attachment of the master elements is equal to the distance between the points of attachment of the slave elements multiplied by the scale factor K_s.

Dimensions of Master and Slave Elements for Following the Positions of the Operator's Hand and Forearm

The dimensions of the master element are determined first if the master and slave elements of a master-slave manipulator follow the positions of the operator's hand and forearm.

1. Knowing the necessary orientation of the tongs of the slave element at each point of the boundary of its work zone, we determine the region of space in which the hand hinge is located when at work.

2. Using the known scale factor K_s, we determine the region of space in which operator's wrist joint is located when performing specified work operations.

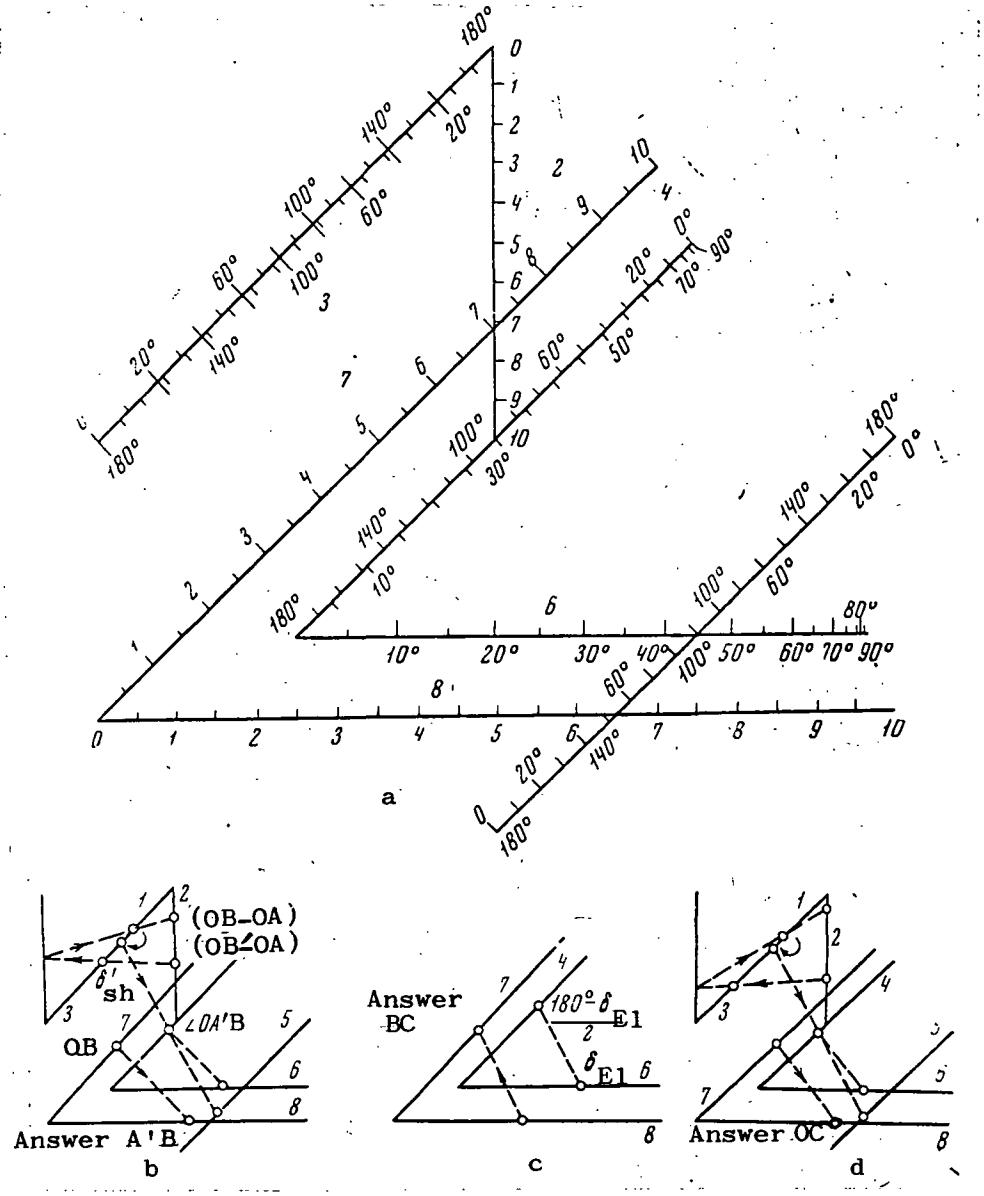

Figure 8. Determination of shoulder and forearm dimensions for given angles of rotation δ_{El} and δ_{Sh}. a - nomogram for determining dimensions; b, c, d - sequence in which nomogram is used.

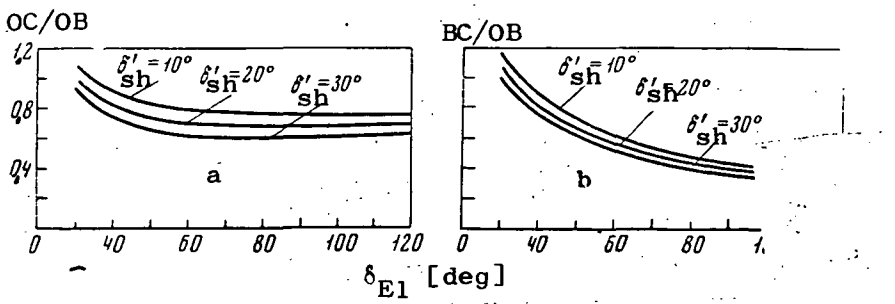

Figure 9. Results of calculations of shoulder and forearm dimensions. a - for ratio OC/OB; b - for ratio BC/OB.

3. Knowing the region of space in which the wrist joint should move, and the dimensions of the operator's forearm, we establish the region of space in which the elbow joint can be located.

4. We determine the distance between the points of attachment of the master elements in terms of the known magnitude of the distance between the points of attachment of the slave elements and the magnitude of K_s.

5. If variant 3 of the kinematic scheme in Figure 4 is used to follow the position of the elbow joint, it is sufficient to find the nearest and farthest positions of the elbow joint (of the elbow hinge of the master element) with respect to the point of attachment of the master element. The difference in these distances is equal to the magnitude of the linear movement in the corresponding degree of freedom. Determined simultaneously are the dimensions of the kinematic shoulder link and the angles of rotation in the degrees of freedom of the shoulder hinge.

6. Using the scale factor K_s, we determine the dimensions of the slave elements. The angles of rotation and the linear movements in the corresponding degrees of freedom of the master and slave elements should be the same.

This calculation procedure provides the dimensions of the master and slave elements of master-slave manipulators built in accordance with the kinematic schemes recommended.

Requirements for Systems for Controlling the Different Degrees of Freedom of the Slave Element of a Master-Slave Manipulator

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Once we have analyzed the peculiarities of the human operator, and the kinematics and dimensions of the master and slave elements of a master-slave manipulator, we can formulate some requirements for the systems for controlling the different degrees of freedom of the slave element.

Power Required for Systems for Controlling the Different Degrees of Freedom

Reference [1] determined the power the human arm develops at the different degrees of freedom of the master element. These data can be used to calculate the power required for systems controlling the different degrees of freedom of the slave element of a master-slave manipulator with the same dynamic properties as the arm. Considering that the load is made up of dynamic and

static components, the maximum power values can be calculated from

$$N^{se}_{max} = N^{30}_{max} \frac{1 + K_s K_{st} K'_w D}{K_s^2 K_{st}^2 K_w (1 + D)}, \qquad (2)$$

where

$$D = \frac{g}{r\ddot{\delta}_{max}};$$

g is the free fall acceleration;

δ_{max} is the maximum acceleration for the corresponding degree of freedom;

r is the coordinate of the center of gravity of the kinematic links of the arm set in motion by the degree of freedom considered;

N^{30}_{max} is the maximum power developed in the corresponding degree of freedom of the master element;

K_s is the scale factor;

K_w is the weight factor, equal to the ratio of the weights of the kinematic links of the arm and slave element set in motion by the degree of freedom considered;

K'_w is a coefficient, the magnitude of which is determined by the ratio of the weights of the load which can be borne by the slave element and the kinematic links of the slave element set in motion by the degree of freedom considered.

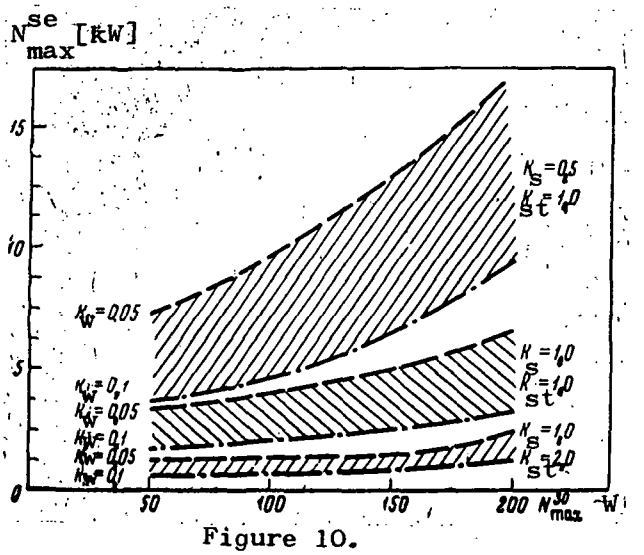

Figure 10.

The weight of the slave element can be taken preliminarily as equal to the maximum load capacity of the manipulator. $K'_w = 3$ for degrees of freedom I and II in the kinematic scheme in Figure 10; $K'_w = 5$ for IV and V; and $K'_w = 15$ for VI, VII, and VIII. Figure 10 gives the powers required for systems for controlling the different degrees of freedom of the slave element of a master-slave manipulator for concrete values of the coefficients. The maximum powers required for systems for controlling a master-slave manipulator are 1.5 - 2.5 kW, given the same magnitude of work zones for master and slave elements ($K_s = 1.0$) and a manipulator load capacity of 40 kg ($K_w = 0.1$). If the magnitude of the work zone for the master elements is half that of the work zone for the slave elements ($K_s = 0.5$), powers increase to 3.5 - 9.5 kW for the same load capacity. /28

These results are valid for a tentative estimate of the powers required for systems for controlling the slave element following the position of the operator's hand.

Input Influences of Systems for Controlling the Different Degrees of Freedom

Considered above were the peculiarities of trajectories over which the tongs of the master element of a master-slave manipulator move. Movement of the tongs can cause movement of any of the degrees of freedom of the kinematic chain of the master element. Eq. (1) therefore describes the input influence of any of the master-slave manipulator control systems. The amplitude of the input influence is different for each of the control systems, and is determined by the distance of the tongs from the axis of the rotation of the corresponding degree of freedom; that is, by the dimensions of the master element.

Maximum Velocities and Accelerations of the Different Degrees of Freedom. Equivalent Working Frequency for Control Systems

Knowing the maximum linear velocities and accelerations of movements of the master element tongs, one readily can determine the maximum angular velocities and accelerations developed in each of the degrees of freedom of the master element's kinematic chain for known kinematics and dimensions

$$\dot{\delta}_{max} = \dot{y}^p_{max}/l;\ \ddot{\delta}_{max} = \ddot{y}^p_{max}/l,$$

where l is the minimum possible distance between the tongs and the axis of rotation of the given degree of freedom.

The equivalent working frequency of the harmonic influence for any of the master-slave manipulator control systems will equal

$$\omega_p = \ddot{\delta}_{max} / \dot{\delta}_{max} = 5\left[\frac{1}{sec}\right].$$

Quality of Transients in Master-Slave Manipulator Control Systems

Characteristic of master-slave manipulator control systems are several operating modes for each of which there are definite requirements with respect to the quality of the transients in the systems.

1. The transport mode, during which the positions in space of the master and slave elements are matched when the master-slave manipulator is energized. The master elements are fixed in space, or are kept immobile by the operator. /29

The quality criterion for the transients in the systems in this mode is the magnitude of the overcontrol, selected on the basis of the characteristics of the work zone for the manipulator's slave elements. If the work zone is free of foreign objects when the manipulator energized the overcontrol can be comparatively great, reaching 20-30%, but if foreign objects or the manipulator carrier housing, are present in the zone when the manipulator is energized, the overcontrol should be 5 to 10%.

2. The following mode, the basic control system operating mode, when following (copying) the movements of the master element. An Eq. (1) type signal is supplied to the control system input, as has been noted above. The control system transients should have a maximum duration of $t_{max} = t_a + t_1$ in order to ensure naturalness in the work of the operator. Here t_a is the duration of the arm movement process. Time $t_1 = 0.2$ second is determined by the delay in the operator's reaction to the incoming external signal (by the latent period). In other words the transients in the control systems should be over when the operator begins the next stage of work.

3. The abrupt change in load mode when the tongs of the slave element come in contact with or, conversely, lose contact with, the object or load being moved during the work process. This same mode is encountered during collisions between the slave element and objects in the work zone.

Given the condition of naturalness of work by the operator, the duration of transients in master-slave manipulator control systems when there is an abrupt change in load should not exceed t_1 = 0.2 second. The magnitude of the relative maximum deviation also is limited because the work is conducted close to objects located within the limits of the work zone.

The requirements for control system for powerful master-slave manipulators formulated in this paper will make it possible to obtain the initial data for their design.

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